

# Testing Stellar Models for M Dwarfs

Honors Research Thesis

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by

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## Abstract

M dwarfs have expected lifetimes of at least 15 Gyr for the main phase of their lives, which is longer than the current age of the Universe. The chemical composition of the surface of an M dwarf, which is nearly constant during this main phase, is the same as the nearby gas of the galaxy in which it formed and at the time that it formed, so M dwarfs create a “fossil record” with which to examine the history and evolution of their host galaxies. This makes M dwarfs extremely important for study, but we do not see enough M dwarfs with few heavy elements, which are the oldest of the M dwarfs, to match predictions of compositions of stars for the local stellar neighborhood. Distances for these M dwarfs are important to accurately determine the extent of this deficiency, but these are difficult to determine accurately for the older M dwarfs that are of the most interest. M dwarfs, and especially older M dwarfs, are also observationally difficult to study in general because they are very dim compared to other stars. In this thesis, we test two different stellar isochrone models, the one by the Dartmouth group and the one by the Padova group, which we will later use to calculate M dwarf distances and investigate the observed discrepancy further. We find that the Padova group’s model fits better with spectroscopic and photometric data taken from two stellar surveys of the Galaxy, APOGEE and SDSS. We then suggest improvements on the tests we have completed and detail the next steps we hope to take in our investigation. We hope that this deep study of M dwarfs will provide more insights into the chemical evolution of the Milky Way, and allow models of stellar formation and Galactic chemical evolution to be improved upon for future use.

## 1. Introduction

In the very early Universe, the gases available for star formation were almost entirely hydrogen and helium. As stars evolve, however, these gases are converted into heavier elements, or metals, and are released into the surrounding medium during the deaths of massive stars or other stellar mass loss mechanisms, to be used in the formation of future stars. As this process has certain timescales governing the rates of conversion, as well as how soon these metals are released and subsequently mixed back into the surrounding gases, the metal content, or metallicity, of a star can give an indication of the age of that star.

Therefore, the chemical content of galaxies, such as our own Milky Way, also changes with time, as more and more metals are released into gases within the galaxy by these stars via mass loss processes such as stellar winds and novae. Stars born at different times in the history of a galaxy will have the same metallicity as the surrounding gas at the time of their births. Thus, combined with a model to predict the metallicity of the gas in a galaxy, the metallicity of a star can serve as an indicator of its age. Similarly, stars with known ages and metallicities can be used to trace out the chemical evolution of their host galaxies.

To make more quantitative predictions about the expected distribution of metallicities, we can use a Galactic chemical evolution model to determine the abundances in the Galaxy at a given place and time and a star formation model to determine how many M dwarfs or other stars we would expect to form at that place and time. The simplest Galactic chemical evolution model, first proposed by Searle & Sargent (1972), is referred to as the *simple model*. Gilmore, King, & van der Kruit (1990) explain that the simple model makes several assumptions. The Galaxy is treated as a closed box initially containing primordial gas of just hydrogen and helium. The mean abundance of the gas is monotonically increasing as a function of time because of our closed box assumption, and the gas is assumed to have perfect mixing, so that it remains chemically homogeneous for all times. The model also assumes

that gases are recycled instantaneously and that the stellar mass function is constant. The resulting equation for this model seems simple, although the actual values of the quantities involved can be difficult to determine. It is given in Gilmore, King, & van der Kruit (1990) as

$$Z(t) = y \ln \left( \frac{M_{\text{tot}}(t)}{M_g(t)} \right), \quad (1)$$

where  $y$  is defined as the yield, or the ratio of the rate at which metals are produced and released by heavy stars to the net rate at which hydrogen is removed from the interstellar medium (ISM),  $M_{\text{tot}}(t)$  is the total mass of hydrogen in stars and the ISM at time  $t$ ,  $M_g(t)$  is the mass of hydrogen in the ISM only at time  $t$ , and  $Z(t)$  is the ratio of the mass of metals to that of hydrogen at time  $t$  in the ISM. Notice that the first assumption of the simple model, that the gas in the box is initially primordial, implies that  $Z(0) = 0$ , which has been included in this solution. The assumptions used in the simple model are known to be false — for instance, the released metals are not instantly mixed back into the surrounding gases, and the Galaxy is not a closed box —, but they do provide a decent starting point for observations, and the model can be modified as we learn more about the true physics involved in the chemical evolution of the Galaxy.

M dwarfs are lower in temperature and in mass compared to all other normal stars, and the most abundant type of star present in our Galaxy. Because they have such low masses and temperatures, they have very long expected lifetimes, longer than the estimated current age of the Universe. This means that we should expect to see M dwarfs of nearly all metallicities, because all of the M dwarfs that have ever been born should still exist today. This makes them ideal in trying to examine the chemical evolution of our Galaxy, because there should be new M dwarfs created at every stage of evolution, creating a “fossil record” of the chemical composition of the Galaxy. Because they are so numerous, as well, we should expect to find this broad range even in the local stellar neighborhood, simply due to the statistics involved in large sample sizes.

While we do see a full range of metallicities in M dwarfs in the local stellar neighborhood, we see a noticeable deficit in the number of the most metal-poor of these stars compared to what we would expect based on the simple model as given by Eq. (1). Woolf & West (2012) call this “the M dwarf problem,” and identify it as being qualitatively similar to the previously defined G and K dwarf problems. G and K dwarfs are the next two star types above M dwarfs in size and temperature. The Sun is a good, well-known example of a G dwarf, and K dwarfs are cooler and smaller than G dwarfs while still being warmer and larger than M dwarfs. There are several possible explanations of this deficit, which are not mutually exclusive. One such possibility is that, as mentioned above, the assumptions made by the simple model are known to be false. They are justifiable assumptions for a first order calculation, but they over simplify the physical processes involved. Biases could also be an explanation, in that M dwarfs, which are already dim, are less luminous for lower metallicities, as can be seen in Fig. 1. This makes low metallicity M dwarfs hard to observe, and so it could be that the low metallicity M dwarfs do exist, and simply are not observed. Also of interest is determining whether the M dwarf problem mentioned by Woolf & West (2012) is quantitatively the same as the G and K dwarf problems, and if not, why stars of different masses would be affected differently.

To investigate this further, large numbers of M dwarfs must be studied. Previous studies of this nature have used very small sample sizes, so it is statistically unclear if the lack of low metallicity M dwarfs is a physical issue or an issue of probabilities with small numbers. The sample must also be volume-complete, so that we do not over or under estimate stars of a certain metallicity because of the luminosity and biases. These stars must have known metallicities and distances, from which we can construct a metallicity distribution function, or MDF, for these M dwarfs. We can use spectroscopy to measure the metallicity of stars in our sample, so we will use the large stellar survey SEGUE, the Sloan Extension for Galactic Understanding and Exploration, a part of the Sloan Digital Sky Survey (SDSS) (Yanny et al.

2009). SEGUE has taken spectra of a large number of M dwarfs, so that our requirement for a large sample size can be fulfilled. For distance measurements, we plan to use photometric data which is also available through SDSS. We can calculate this distance via the distance modulus, which relates the apparent brightness, or magnitude  $m$ , of a star a distance  $d$  away to the absolute magnitude  $M$ , defined as the magnitude it would have at  $d = 10$  pc, via the formula

$$m - M = 5 \log \left( \frac{d}{10 \text{ pc}} \right), \quad (2)$$

or, solving for  $d$ ,

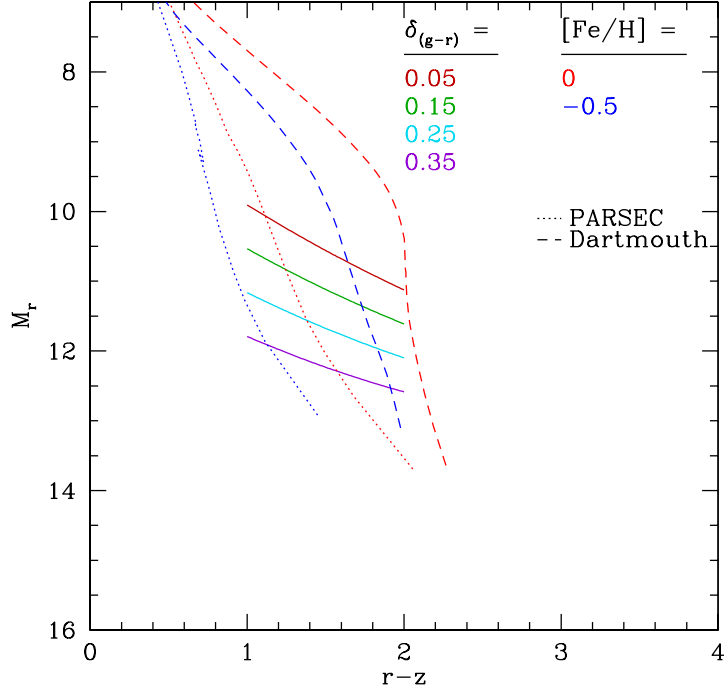
$$d = 10^{0.2(m-M+5)} \text{ pc} \quad (3)$$

(Ryden & Peterson 2010). SDSS, however, only measures and provides apparent magnitudes of the stars in its database, so we will use a stellar isochrone model to determine the absolute magnitude based on color and metallicity. It is important that these models provide photometric data in the *ugriz* filters used by SDSS. While there are other photometric surveys available using other, similar photometric systems, SDSS is the largest scale project available for our use, so it is an invaluable resource. However, because the filters are in a vacuum, there are subtle differences, and this means that we must calibrate the photometry we have in SDSS rather than using the filter systems of other telescopes. Here we are testing two models which are known to provide *ugriz* absolute magnitudes on all of their grid points, the one by the Dartmouth group (Dotter et al. 2008) and the PARSEC code by the Padova group (Bressan et al. 2013). Bochanski et al. (2013) compare absolute magnitude variations which they measured using statistical parallaxes with two different metallicity indicators, and give an empirical equation for absolute magnitude in terms of  $r-z$  and their empirically found metallicity indicator  $\delta_{(g-r)}$ . This equation is valid for  $1.0 < r - z < 2.0$  and  $0.0 < \delta_{(g-r)} < 0.5$ . Fig. 1 shows the absolute magnitude versus  $r-z$  for various values of this  $\delta_{(g-r)}$  as well as for various values of metallicity for the two models tested here, where

metallicity  $[Fe/H]$  is measured as

$$[Fe/H] = \log \left( \frac{N_{Fe,*}}{N_{Fe,\odot}} \right) - \log \left( \frac{N_{H,*}}{N_{H,\odot}} \right). \quad (4)$$

In this equation,  $N_{Fe,*}$  is the number of iron atoms in the star,  $N_{Fe,\odot}$  is the number of iron atoms in the Sun, and  $N_{H,*}$  and  $N_{H,\odot}$  are the corresponding quantities for hydrogen, so that solar metallicity is given as  $[Fe/H] = 0$ . While we have not yet calibrated the empirical  $\delta_{(g-r)}$  with  $[Fe/H]$ , we can see that the two models do not agree well with the empirically determined equations.



**Fig. 1.**—  $M_r$  vs.  $r - z$  for various metallicities and various  $\delta_{(g-r)}$  values. The  $\delta_{(g-r)}$  values and their corresponding absolute magnitudes are calculated according to Bochanski et al. (2013). The other lines are taken at  $[\text{Fe}/\text{H}] = 0.0$  (red) and  $[\text{Fe}/\text{H}] = -0.5$  (blue) for Dartmouth (dashed lines) and PARSEC (dotted lines). See Eq. (4) for the definition of  $[\text{Fe}/\text{H}]$ . There is a correlation between the empirical  $\delta_{(g-r)}$  values and  $[\text{Fe}/\text{H}]$ , but we have not yet done the calibration to determine the relationship. Notice the lack of agreement between the models and the empirical lines.

There are a few issues which must first be resolved, however, and that is what this thesis is focused on, thus laying the groundwork for future studies to calculate an accurate, volume-complete M dwarf MDF. The stellar isochrone modeling codes solve for various properties of stars, such as radius and luminosity, based on a given mass, composition, and age. In order to then predict the surface temperature of the star, and thus the star’s color, they must include a stellar atmosphere. But, as we can see from the many band features in the example spectra in Fig. 2, these atmospheres involve complicated chemical compositions that can be

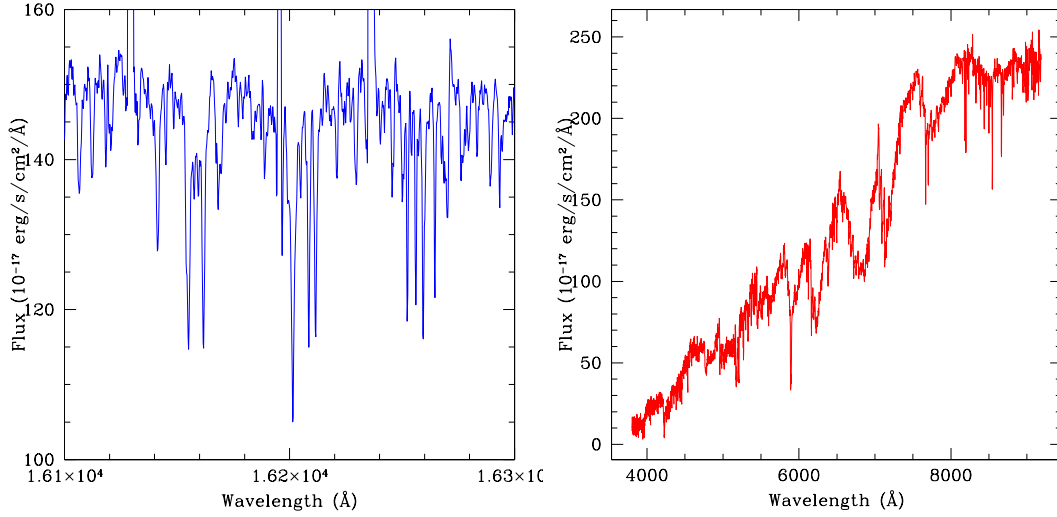


difficult to model accurately. So we will first need to determine which of these models gives the best predictions of photometry in the *ugriz* filters used by SDSS before using this model to determine the absolute magnitudes and distances for our sample. We will do this by first comparing the model predictions for the colors of stars with certain effective temperatures and metallicities for those stars that have measured photometry in SDSS as well as known stellar parameters which have an effect on observed color. A star’s effective temperature is the temperature it would have if it were radiating as a perfect blackbody based on its luminosity, and can be found from the equation for luminosity,

$$L = 4\pi R_*^2 \sigma_{SB} T_{\text{eff}}^4, \quad (5)$$

where  $R_*$  is the star’s radius,  $\sigma_{SB} \approx 5.67 \times 10^{-5} \text{erg} \cdot \text{cm}^{-2} \text{K}^{-4} \text{s}^{-1}$  is the Stefan-Boltzmann constant,  $L$  is the luminosity of the star, and  $T_{\text{eff}}$  is the effective temperature of the star (Ryden & Peterson 2010).

While we want to use the large data sets available to us in SEGUE, for accurate testing of the isochrone models, SEGUE will not be sufficient. SEGUE takes spectra in the optical wavelengths, where M dwarf spectra are complicated because they include more of the absorption lines of molecules rather than single atoms. However, another survey in SDSS, the Apache Point Observatory Galactic Evolution Experiment, or APOGEE (Eisenstein et al. 2011; Ahn et al. 2014), which samples in infrared wavelengths could be helpful in this regard. The two spectra of Fig. 2 show a typical M dwarf spectrum sampled by APOGEE and SEGUE for comparison.

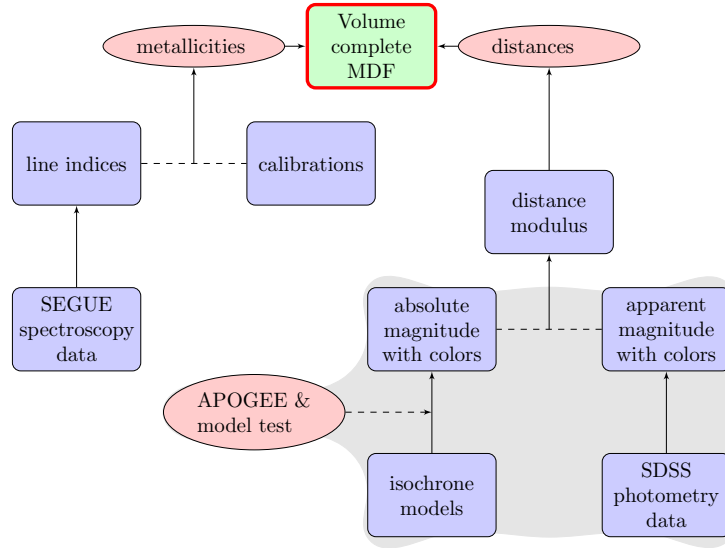


**Fig. 2.**— Sample spectrum from APOGEE (left) and SEGUE (right) for 2M16393824+3550337, a randomly selected M dwarf. The APOGEE spectrum is zoomed in enough to observe individual features. While both spectra show noise, the APOGEE spectrum, taken in the infrared with higher resolution, is much less complicated than the SEGUE spectrum, taken in the optical, because of the presence of more molecular band features in the optical spectrum as compared to the infrared spectrum, which contains mostly single atom band features. This is why the parameters from APOGEE are more reliable, and why we hope to use APOGEE to find the best model to use and create a calibration for the SEGUE parameters.

APOGEE also has a much higher spectral resolution, typically about  $R = \frac{\lambda}{\Delta\lambda} = 22,500$  (Ahn et al. 2014) as compared to the about 1,800 typical for SEGUE (Eisenstein et al. 2011). So while APOGEE is a smaller survey, sampling less stars over a smaller portion of the sky, it has much more reliable parameters for calibrating and testing our models.

To summarize, we use data from APOGEE as a calibration against which we can test our stellar models to make sure they make accurate predictions about the colors and luminosities of these stars, which is the focus of this thesis. After this is done, we will be able to use the best models and SDSS photometry to calculate distances using the distance modulus

given by Eq. (3) to the stars in the larger sample collected from SEGUE. We will also use the APOGEE stars to find a calibration for metallicities based on various lines seen in the spectra of the stars — such as those for CaH2, CaH3, and TiO5 —, and we will later use the SEGUE spectra to derive metallicities for the stars in our larger sample. With the large volume-complete sample that we will end up with, we will be able to re-examine the M dwarf problem of the Galaxy. A schematic representation of this project is shown in the flow chart of Fig. 3, with the current focus being the area with the gray background in the lower right hand corner.



**Fig. 3.**— Flow chart for the goals of the broader project that we hope to complete after the work of this paper. The subject of this paper is the area with the gray background in the lower right corner.

In §2, we talk about how we collected the data for our analysis, for both the models (§2.1) and the stars from APOGEE and SDSS (§2.2). We go on to discuss the results of the analysis in §3, and §4 summarizes the main conclusions we have drawn. The next steps that we hope to take are described in §5, and more specific detail about the data collection can be found in §6.

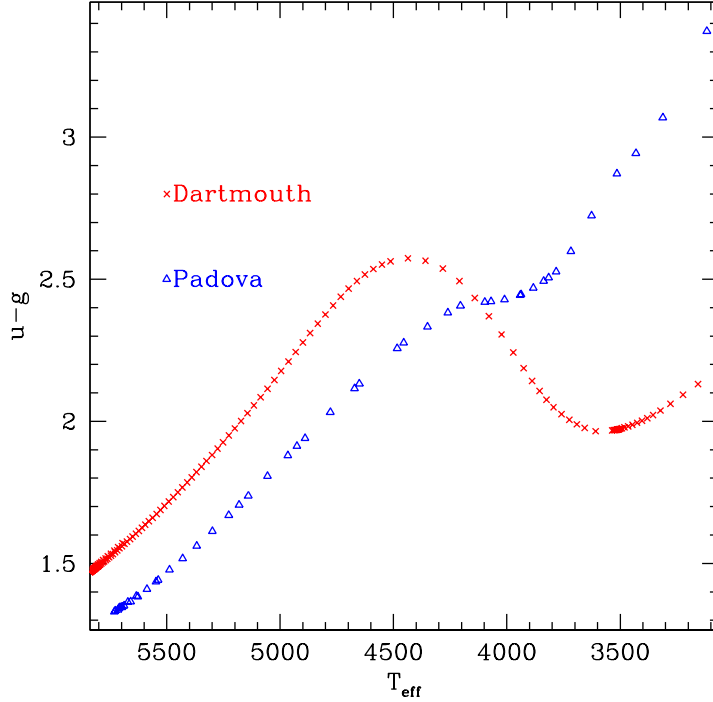
## 2. Data Collection

### 2.1. Isochrone Models

The Dartmouth and Padova groups have web-based applications for gathering model grids which allow users to specify desired inputs as well as select the photometric system used for the magnitudes. The specific inputs we used were for SDSS *ugriz* magnitudes given for stars of age 10 Gyr with various metallicities. M dwarfs have an expected lifetime of at least 15 Gyr on the main sequence, or the main phase of their life, during which we can safely make the assumption that the chemical compositions of their atmospheres remain relatively unchanged. So choosing just one age sometime during the main sequence lifetime of an M dwarf should be sufficient for us to determine the chemical composition of the atmosphere of the M dwarf. The metallicity indicator we used was  $[\text{Fe}/\text{H}]$  (see Eq. (4)), but it should be noted that the Padova group uses metallicities  $Z$  instead, so a conversion was needed from  $[\text{Fe}/\text{H}]$  to  $Z$  for the proper metallicities. This conversion was taken to be

$$\log \left( \frac{Z}{Z_{\odot}} \right) = [Fe/H]. \quad (6)$$

The Padova group quotes a solar metallicity used for PARSEC of  $Z_{\odot} = 0.0152$  (Bressan et al. 2013; Caffau et al. 2011). We used metallicities from  $[\text{Fe}/\text{H}] = 0.0$  dex down to  $[\text{Fe}/\text{H}] = -2.0$  dex in increments of 0.5 dex. We also separated dwarf and giant stars using the condition that  $\log(g) > 4.0$  for dwarfs and  $\log(g) < 4.0$  for giants. We then made plots of various color indices versus temperature. The color indices we focused on were  $u-g$ ,  $g-r$ ,  $g-i$ , and  $r-i$ , and we found that the most discriminatory of these was  $u-g$ . As an example, Fig. 4 shows  $u-g$  versus temperature for dwarfs of  $[\text{Fe}/\text{H}] = 0.0$  dex for both the PARSEC and Dartmouth models.



**Fig. 4.**— Plot of  $u-g$  vs. temperature for model grid points. The plot shown is only for dwarfs of  $[\text{Fe}/\text{H}] = 0$  dex. The red points indicate the Dartmouth model, while the blue points indicate PARSEC.

With this thought in mind, we only used  $u-g$  color for comparing the models with the data, although we collected information on the apparent magnitudes in all of the bands.

## 2.2. Stellar Sample

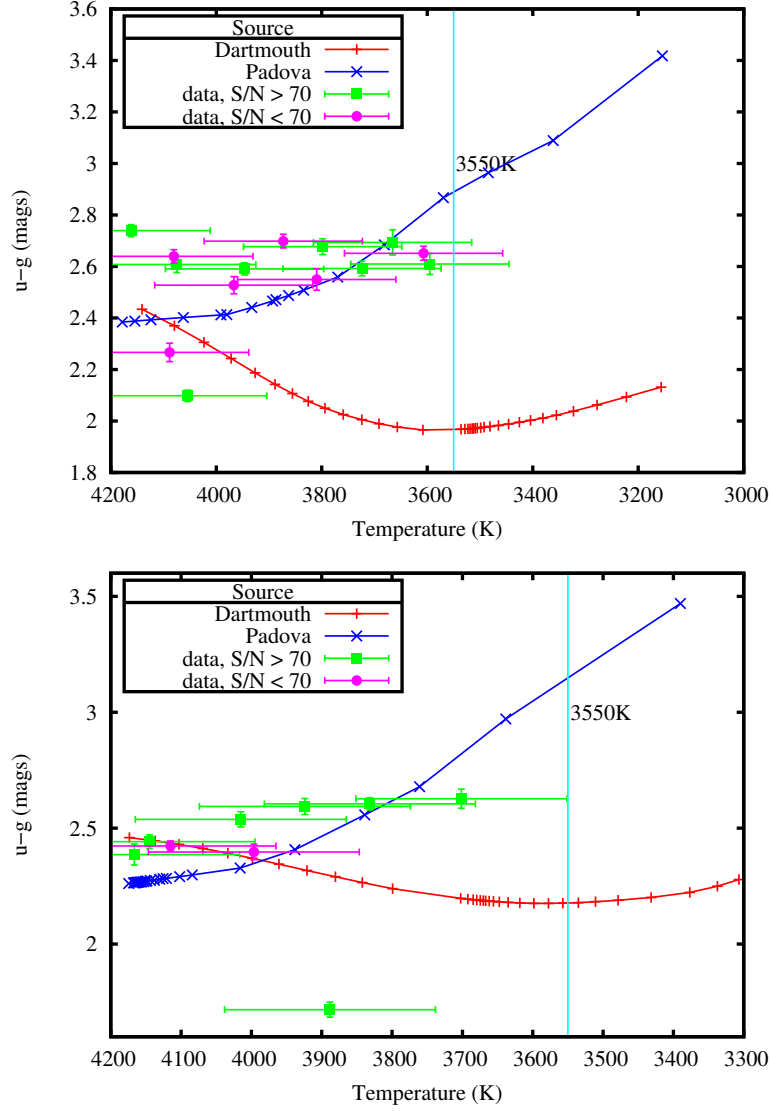
As mentioned above in §1, APOGEE targets were used because of the more reliable parameters. APOGEE is a currently ongoing survey, so not all of the data that it will collect have been released yet. The data that we used was only from the first year of run time for APOGEE, and it included a total of 59,609 stars. We needed to cut these based on several parameters. First, M dwarfs have effective temperatures of  $T_{\text{eff}} \approx 2700 \text{ K} - 4100 \text{ K}$ .

However, APOGEE temperature measurements for stars below about 3550 K are unreliable at this time, and so the temperature cut that we used was  $T_{\text{eff}} = 3550 \text{ K} - 4200 \text{ K}$ . This left only 150 M stars, both giants and dwarfs. We also needed the photometric data from SDSS, so only those stars with matches in the SDSS database were kept. To find these, we used an SQL query on the Catalog Archive Server Jobs System, or CasJobs, which supplied us with data from the database that matched our criterion (see §6). Because we already knew that we wanted to compare  $u-g$  with temperature, we made a further cut to only include stars whose SDSS images were unsaturated through the  $u$  and  $g$  filters. This was necessary because of the difference in observational techniques used. APOGEE targets bright infrared stars selected from the 2MASS infrared photometric survey. The optical photometric survey of SDSS observes patches of the sky for about 54 seconds through each of the  $ugriz$  filters, so bright stars become saturated. When this happens, the measurements for the magnitudes become inaccurate, so we could not use stars with saturated images for testing the stellar models. This was another reason to only use  $u-g$  color for the comparisons, because most other colors would not give us as many stars with clean photometry. For this cut, we checked for flags used by SDSS during observations, which signaled saturation in the various photometric bands, and removed any stars for which this flag was set. With these criterion, we still occasionally had some APOGEE stars with multiple matches in SDSS, most likely due to saturation or multiple visits. In this case, we selected the closest bright neighbor so that each APOGEE star only had one set of matches. After these cuts, we had a sample of 37 stars with clean photometry and APOGEE spectra.

### 3. Results

We binned the data from APOGEE+SDSS by  $[\text{Fe}/\text{H}]$  in bins with centers at every 0.5 dex and also separated the stars as dwarfs or giants using a cut on surface gravity as in

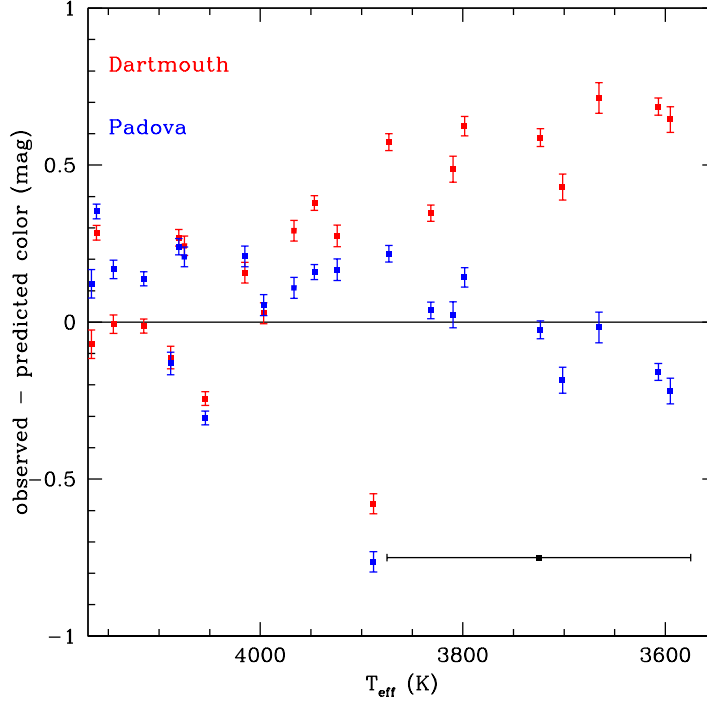
§2.1. However, we only had M dwarfs in the bins for  $[\text{Fe}/\text{H}] \in [-0.25, 0.25)$  dex and  $[\text{Fe}/\text{H}] \in [-0.75, -0.25)$  dex. This is unsurprising for a sample of only 37 stars, and we plan to have a broader range of metallicities when we start to use the larger sample from APOGEE as well as when we begin using data from SEGUE. The  $u-g$  color for these stars was plotted versus temperature, with the models plotted with lines in the same plots for easier comparisons. Errors on the temperatures for the data points were taken to be 150 K, as reported for APOGEE (Eisenstein et al. 2011; Ahn et al. 2014). The vertical lines show the 3550 K temperature cut off used for the APOGEE stars. The two plots of Fig. 5 show both of the metallicity bins that contained M dwarfs, and the stars were sorted for  $S/N > 70$  or  $S/N < 70$ .



**Fig. 5.**— Color ( $u-g$ ) vs. temperature for dwarfs of  $-0.25 \text{ dex} \leq [\text{Fe}/\text{H}] < 0.25 \text{ dex}$  (top) and  $-0.75 \text{ dex} \leq [\text{Fe}/\text{H}] < -0.25 \text{ dex}$  (bottom). The vertical line marks the cut off temperature of 3550 K used for the APOGEE data. The models are drawn with connecting lines for easier comparisons of the data with the models, and the red line is the Dartmouth model while the blue line is the PARSEC model. The data were also split by S/N in each plot. We can qualitatively see that the data in general agree more with the PARSEC model than the Dartmouth model.



From these, we can already see that neither model fits the data completely successfully. However, qualitatively, we can say that the PARSEC model fits the data better than the Dartmouth model. We decided to do a numerical analysis for the goodness of fit to get a more quantitative result. We used the cubic spline interpolating function provided by the GNU Scientific Library to interpolate the model grids for each data point from APOGEE+SDSS. By doing this, we were able to find the colors predicted for each star by the models. We could then compare the observed and predicted colors versus temperature. Fig. 6 shows a plot of the difference in observed and predicted colors (observed - predicted color, O-P) for each model versus temperature. The black line represents where the O-P value for color is zero. From this we can clearly see that the PARSEC model is a better fit to the data than the Dartmouth model, as more of the O-P colors for PARSEC (blue data points) lie closer to zero than for Dartmouth (red data points), indicating that the colors predicted by PARSEC are in general closer to the observed colors than the colors predicted by Dartmouth.



**Fig. 6.**— Difference in observed and predicted colors for both models. The colors were predicted using an interpolation of the model grid points for both the PARSEC and Dartmouth models. Blue points represent the PARSEC model, and red points represent the Dartmouth model. The line represents a difference in color of zero. With more of the PARSEC points close to zero, it is clear that PARSEC fits the data much better, as demonstrated by the  $\chi^2$  values shown below. The black data point with the error bars represents the x errors on all data points, taken to be 150 K as reported for APOGEE (Eisenstein et al. 2011; Ahn et al. 2014).

We also computed  $\chi^2$  values for both models, with

$$\chi^2 = \sum_i ((O - P)_i)^2, \quad (7)$$

where the sum is over stars  $i$ . When we do this calculation, we find the  $\chi^2$  values listed below. This again shows that PARSEC, with a  $\chi^2$  of about 1.55, is a better fit to our data than the Dartmouth model, with a  $\chi^2$  of about 5.28. However, it also shows that our previous intuition that neither model fits very well with the data is true.

PARSEC : 1.54953

Dartmouth : 5.28478

#### 4. Conclusions

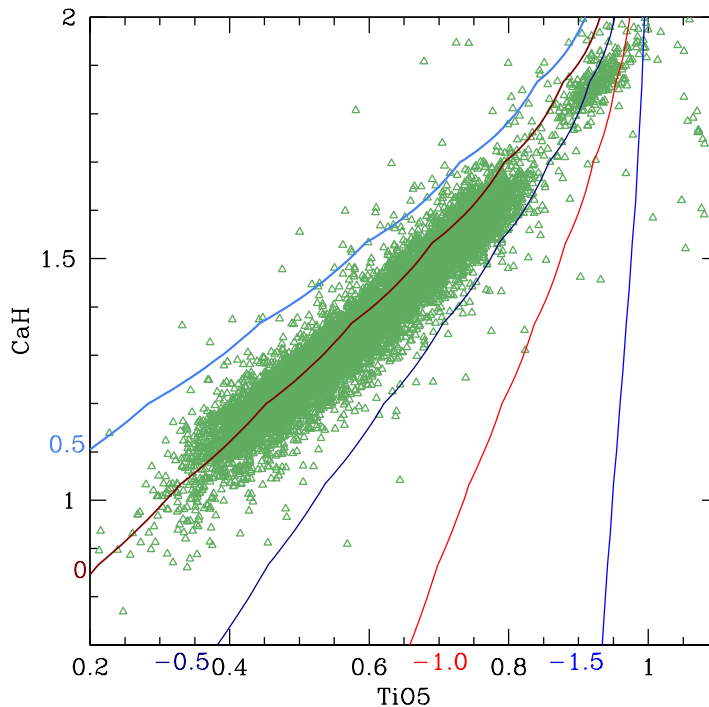
We have tested two different stellar isochrone models, the PARSEC code by the group from Padova and the code by the group from Dartmouth, against data taken from APOGEE+SDSS to see how well the models predict the colors reported by SDSS. Using interpolation of the model grids and a simple  $\chi^2$  analysis, we have determined that while neither model fits completely successfully, the PARSEC code does predict the  $u-g$  color, where we see the most difference between the models, better than the Dartmouth model for our sample of 37 stars with clean photometry and APOGEE spectra. We can now use the PARSEC model for calculating distances for SEGUE stars as we continue with our overall project as outlined by Fig. 3.

#### 5. Future Work

While this analysis can provide us with a stepping stone for the rest of the project, it is not yet perfect. While we do not need as large of a sample size for testing the models, there is more data available for our use. For instance, as mentioned above, APOGEE is currently running. While we only had the first year data available to us at the onset of the project, the second year data has now be released, and the third year data is currently being collected. It is our hope that we can incorporate these new data into the current analysis, providing us with a better test of the models with more than 37 data points.

We also have only tested two models, those by the Dartmouth group and the Padova group, so far. We could potentially look for more models that might fit the data even better, although we have found this to be more difficult than it would seem, as the models need to provide photometric data in the *ugriz* filters, as mentioned above. While testing more models could provide some benefit, however, the PARSEC model seems to match the data well enough that we feel confident using it in the coming steps of the project.

The next steps of the project are to collect the data from SEGUE and begin to calculate metallicities using our calibrations and distances using absolute magnitudes that we find from the PARSEC model. We plan to use a few sets of criterion based on various plates of SEGUE (Yanny et al. 2009) to create a larger data set with a broader range of metallicities than previous studies of a similar nature, such as Woolf & West (2012). They used only the Munn “special plates” from SEGUE (Yanny et al. 2009) for their data sample, which target objects in the thin and thick disk. We plan to use these plates plus the two sets of “merged” plates, which include all point sources in the target areas of those plates. We have chosen these plates to provide us with more M dwarfs, and especially more metal poor M dwarfs, while avoiding objects labeled as M dwarfs by SDSS which are actually galaxies or QSOs. We have already begun this process, although we only have a small amount of the data we eventually hope to find, and at this point we have not yet completed the search for the metal-poor M dwarfs that we hope to also find in the SEGUE catalog. We have started using various spectral line indices to calculate metallicities with calibrations given in Mann et al. (2013).



**Fig. 7.**— Preliminary results for determining metallicities of the first set of M dwarf stars taken from the SEGUE catalog. The lines indicate lines of isometallicity, with the numbers labeling the metallicity to which the lines correspond. We do not see many metal-poor M dwarfs in this sample, but we do see a much larger data set, 7,351 stars compared to 4,141 from Woolf & West (2012), and we still have more criterion that we hope to use to fill in the low metallicity region of the plot. The lines were calculated using calibrations taken from Mann et al. (2013), although we hope to use updated calibrations in the future.

See §6 for more information on how the data are being collected from SEGUE.

Mann et al. (2013) suggest an updated calibration for metallicity, and while we did not use the updated calibration in calculating the isometallicity lines in Fig. 7, we plan to do so as we continue the project. The results we have found so far are promising, and we have even been able to start calculating some distances for these M dwarfs, and determining a range in which we see both metal-rich and metal-poor M dwarfs, although we still have much more

work to be done in this area.

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## 6. Supplementary Materials

The data collected from SDSS and from SEGUE so far have been collected using SQL queries on CasJobs. After the data from APOGEE had been cut based on temperature, the table was uploaded to CasJobs, although we discovered that it also had to be split into several smaller tables because of the memory capacity limits enforced by CasJobs. The query below shows an example of one used to match SDSS data with APOGEE data that we had already collected.

```
select p.psfMag_u , p.psfMagErr_u , p.extinction_u ,  
       p.psfMag_g , p.psfMagErr_g , p.extinction_g ,  
       p.psfMag_r , p.psfMagErr_r , p.extinction_r ,
```

```

p.psfMag_i , p.psfMagErr_i , p.extinction_i ,
p.psfMag_z , p.psfMagErr_z , p.extinction_z ,
p.ra , p.dec
into mydb.Photo_ra_dec_lines_145_147
from mydb.ra_dec_l_145_147 t, PhotoObjAll p
where p.type=6 and p.psfMag_g < 21
and sqrt((t.RA_PLATE-p.ra)*(t.RA_PLATE-p.ra)*
cos(t.DEC_PLATE*3.14159/180)*cos(t.DEC_PLATE*3.14159/180)
+(t.DEC_PLATE-p.dec)*(t.DEC_PLATE-p.dec)) < 1.5

```

The type condition specified that we only wanted stars, and we also specified that we wanted only those stars with  $g$  band magnitudes less than 21 mags and within  $1.5^\circ$  of the location of the APOGEE star. We later realized that we needed a way to cut any stars that were saturated, and for this we took the same matched data and queried on it again, although we were now able to use just one table. This new query involved asking for the flags on each band, which we could then read and convert from hexadecimal to determine which flags were set and remove any saturated stars.

```

select
p.psfMag_u , p.psfMagErr_u , p.extinction_u , p.psfMag_g ,
p.psfMagErr_g , p.extinction_g , p.psfMag_r , p.psfMagErr_r ,
p.extinction_r , p.psfMag_i , p.psfMagErr_i , p.extinction_i ,
p.psfMag_z , p.psfMagErr_z , p.extinction_z , p.ra , p.dec ,
p.flags_u , p.flags_g , p.flags_r , p.flags_i , p.flags_z , p.flags ,
sqrt((t.RA_AP - p.ra)*(t.RA_AP - p.ra)*cos(t.DEC_AP*3.14159/180)*
cos(t.DEC_AP*3.14159/180) + (t.DEC_AP - p.dec)*(t.DEC_AP - p.dec))*3600
as distance , t.OBJ_AP, p.objID , p.parentID

```



```

into Photo_ra_dec_matched
from ra_dec_matched as t, Photo_ra_dec as p
where sqrt((t.RA_AP - p.ra)*(t.RA_AP - p.ra)*cos(t.DEC_AP*3.14159/180)*
    cos(t.DEC_AP*3.14159/180) + (t.DEC_AP - p.dec)*(t.DEC_AP - p.dec))*3600
    < 3.0

```

In this query, we further restricted the distance to be within 3'' of the star. We then were able to use a C++ code to check these flags, and thus make our additional cuts.

The SEGUE data collected so far have been collected from two chunks of SEGUE, munn49 and merged48 (Adelman-McCarthy et al. 2006). These chunks were selected for including “all point sources” and “thin/thick disk”, respectively. We also limited our query to those objects classified as stars.

```

select sp.CaH2side, sp.CaH2err, sp.CaH2mask, sp.CaH3side, sp.CaH3err,
    sp.CaH3mask, sp.TiO5side, sp.TiO5err, sp.TiO5mask, s.ra, s.dec,
    s.plate, s.mjd, s.fiberID, s.chunk, s.class, s.subClass, s.specObjID
into mydb.chunks
from SpecObj s join sppLines sp on sp.SPECOBJID = s.specObjID
where s.class = 'STAR'
    and (s.chunk = 'chunk48' or s.chunk = 'chunk49')

```

From here, we were also able to apply a color cut, for which we used  $g-r > 1.1$ , as shown below.

```

select t.CaH2side, t.CaH2err, t.CaH2mask, t.CaH3side, t.CaH3err,
    t.CaH3mask, t.TiO5side, t.TiO5err, t.TiO5mask, t.ra, t.dec,
    t.plate, t.mjd, t.fiberID, t.chunk, t.class, t.subClass,
    t.specObjID, (s.psfMag_g - s.psfMag_r) as gr

```

```
into mydb.chunks_cut  
from mydb.chunks t join SpecPhoto s  
  on (s.plate = t.plate and s.mjd = t.mjd and s.fiberID = t.fiberID)  
where s.mode = 1 and s.psfMag_g - s.psfMag_r > 1.1
```

This query gave us 16,154 stars. However, some additional cuts were needed so that only stars with good line index measurements were used. We had two ways of determining this, using the line index masks and the errors. The line index masks are reported by SEGUE, and can have a value of either 0 for good or 1 for bad. The errors are also reported by SEGUE, but there were some stars with reported errors of -9.999, and we assumed that these stars did not have accurate measurements for the line indices. After using these two cuts, we were left with 7,351 stars, which are plotted in Fig. 7.